MINERAL PROVINCES AND METALLOGENETIC EPOCHS IN WESTERN AUSTRALIA.

PRESIDENTIAL ADDRESS, 1939.

By EDWARD S. SIMPSON, D.Sc., B.E., F.A.C.I.

Read 11th July, 1939: Published 26th February, 1940.

INTRODUCTION.

The most superficial consideration of the distribution of metallic ores, and other commercial minerals, throughout the world discloses the fact of their very irregular and unequal distribution. A closer study of these economically valuable resources in the field reveals the further fact that any particular mineral may be found in one region only in very ancient rocks, and in another only in much more recent ones. From these observations arose the twin concepts of metalliferous provinces in the land areas of the globe, and of metallogenetic epochs in the earth's history. A logical expansion of the originally restricted idea of metalliferous provinces leads to the more general concept of mineral provinces, which embraces the distribution of non-metallic as well as metallic minerals.

A thorough understanding of the local application of both these ideas is essential to the systematic development of any country's mineral resources, and the logical planning of its future industrial expansion. Incidentally it has led to much heart burning and covetousness on the part of progressive peoples.

MINERAL PROVINCES.

Studying first in detail the idea of mineral provinces, we find that certain more or less well-defined areas of land, ranging from, say, 1,000 square miles to 100,000 or more square miles, are abnormally rich in one valuable mineral, often in several, and completely devoid of, or very poor in, many others. There appears, therefore, to be, firstly, a defined and restricted distribution in each continent of each valuable metal or mineral, and secondly, an incompatibility of occurrence between certain pairs or sets of minerals, as for example, between gold and tin, copper and coal, asbestos and lead. Such incompatibilities are, in fact, commonly observed and well established as the outcome of natural laws. They are not, however, invariable, as from time to time apparently incongruous associations are recorded. The exceptions, however, are sufficiently rare not to upset the practical application of the general law, but serve only to emphasise the complexity of all natural processes, and the imperfection of our knowledge of them. In general, the obvious natural law appears to be that if any two minerals have their own distinctive, and invariable, or almost invariable, modes of origin, and if these modes are quite different from one another, then the two minerals will not be found in commercial abundance in the same area. To anticipate somewhat a latter section of this address, exceptions to this law may usually be traced to two very different conditions prevailing in the region at two different ages of the earth's history. In certain portions of South Africa for example, two usual incompatibles, diamonds and gold, are found plentifully in one province, the explanation of which is that they were formed at different epochs under different prevailing conditions.

In contradistinction to these incompatibilities there are many well-established compatibilities of occurrence based on genetic identities. Thus regions rich in lead are very often rich also in zinc and silver, and others rich in tin are not uncommonly rich in tungsten, tantalum or lithium minerals. This arises from the fact that the members of each of these two dissimilar groups are derived in the same way by characteristic types of pneumatolytic and hydrothermal action from similar magmas. Again, provinces rich in chromite will frequently be found to be rich in platinum, or nickel or chrysotile asbestos, since all these are usually segregated *in situ* from similar ultrabasic magmas. In other provinces coal and iron carbonate ores are abundant, in others again sulphur, gypsum and petroleum, since both groups are originated by sedimentation under similar conditions in shallow restricted areas of water.

The science of economic mineralogy, building on the fundamental observations and deductions of von Cotta[1], Phillips[2], Posepny[3], Van Hise[4], Lindgren[5], and others, has now reached the stage at which a comprehensive list of the usual compatibilities and incompatibilities can be drawn up with a considerable degree of assurance. Furthermore, State and exploratory geological surveys are sufficiently advanced over large areas of the globe to enable many mineral provinces to be accurately defined.

It is of the greatest practical importance to seek to discover what causes govern the distribution of metalliferous or earthy mineral provinces, and the compatibilities and incompatibilities traceable within each of them, so as to be able to apply the results of these researches to our own State in the direction and control of the mining industry. It is here necessary to emphasise the fact that the average amount of the valuable metals and non-metallic elements in the whole of the earth's crust that is within the range of mining operations is in most cases extremely small. An actual estimate is given in Table 1, compiled from the publications of F. W. Clarke, H. S. Washington, and others[9] [12]. Even the most abundant of the valuable metals aluminium, iron, potassium and magnesium are, on the average, present in amounts which would not constitute a workable deposit. And others of our common metals, such as copper, lead, zinc and tin, are in such small quantities that if evenly distributed through the crust, they would cost as much as gold to produce.

AVERAGE PROPORTIONS OF METALS, ETC., IN EARTH'S CRUST.

Aluminium ...	7·5	per cent.	Sodium ...	2·6	per cent.
Iron	4·7	,,	Potassium ...	2·4	,,
Calcium ...	3·4	,,	Magnesium ...	1·9	,,
Titanium ...	·6	,,	Barium ...	·04	,,
Phosphorus ...	·1	,,	Chromium ...	·04	,,
Manganese ...	·09	,,	Nickel ...	·03	,,
Carbon ...	·08	,,	Copper ...	·01	,,
Sulphur ...	·06	,,	=	100	parts per million
Zinc	40	parts per million	Boron	10	,, ,,
Cobalt	30	,, ,,	Beryllium ...	10	,, ,,
Lead	20	,, ,,	Arsenic ...	10	,, ,,
Tin	5	,, ,,	Molybdenum ...	< 1	part per million
Antimony ...	< 1	part per million	Mercury ...	< 1	,, ,,
Bismuth, Tungsten, Tantalum, Niobium, Silver, Gold, Platinum					Less than 1 part in ten millions.
Radium					About 1 part in a billion.

Fortunately for the development of our civilisation, nature has been at work through the ages making local concentrations of metals and minerals that we need. And this has been done on such a scale and to such good effect that we are able to obtain without great difficulty and at reasonable expense the supplies of metals and minerals that we require. In this connection I do not intend to enter into the old, and still intermittently disputed argument, as to whether the workable concentrations of heavy metals were ultimately derived from deep-seated volcanic magmas, or from the adjacent rocks on the same horizons as the deposits themselves[3, 13]. I will merely assume that this argument will ultimately be satisfied, as so many others have been, by the realisation that both causes are effective to varying degrees in various places. In the former case the medium by which the concentration is effected is the hot water and steam given off by the cooling igneous magma, and in the latter either similar agencies, or the comparatively shallow circulation of atmospheric water. For the purpose of our present argument, one must realise that the intense concentraion of an element by nature in a limited area has meant that a much larger area surrounding it has been starved of that element. This is a fact having an important bearing on the theory of mineral provinces.

There are four obvious influences, all of paramount importance, in localising commercially valuable mineral deposits. These are:

(1) The nature and origin of the immediate "country," *i.e.*, the actual enclosing rock or rocks; (2) the nature of the igneous rocks underlying and closely surrounding the rock matrix; (3) the dynamic history throughout geological time of the individual district, or province; (4) the extent to which rock formations containing valuable mineral deposits, or capable of developing them, have been overlaid by later rocks of a different, and often entirely unfavourable nature.

Let us consider in more detail these fundamental influences. Broadly speaking, workable deposits of minerals may be divided into two main classes, (1) those originating from subterranean action, including volcanic intrusion and fluid circulation, (2) those originating from surface erosion and subsequent deposition. The former fall into two groups: (A) Those derived by segregation in an original molten matrix, *e.g.*, platinum, chromite, ilmenite; (b) those derived mostly from igneous magmas, but transported elsewhere by vapours or solutions before deposition, *e.g.*, gold, cassiterite, lithium minerals, etc. Class (2), of course, embraces such well-known minerals as coal, salt, limestone, and many iron ores.

These facts profoundly influence the regional distribution of mineral deposits, for whilst minerals of Class (2) can only be found in areas occupied by sedimentary rocks, and in many cases are confined to those of certain restricted ages, minerals of subterranean origin are found not only in areas where igneous rocks outcrop, but in the case of that most important group, (1)B, in areas of all kinds of rocks, both igneous and sedimentary, though usually at a limited vertical or horizontal distance from igneous rock of some kind or other.

The influences controlling mineral deposits of igneous origin are of especial importance in Australia. They include both the gross compositional type of the igneous rocks of a district, and the variable distribution in these of traces of what are, broadly speaking, rare elements.

The members of the compatible group platinum-chromite-chrysotile asbestos-magnesite are, for example, almost without exception confined to the ultrabasic rock group, characterised by a high content of magnesia and a low content of alkalis and alumina. The elemental materials for forming the three last minerals are comparatively common constituents of all such rocks, but platinum is a "trace element" of very capricious distribution, even in its favourable matrix, and hence workable deposits are confined to a very small percentage of the known areas of ultrabasic rocks.

This variable distribution of trace elements of human value in magmas of similar type is one of the most important factors in originating and defining mineral provinces. In the original magmas from which so many commercially important concentrations of metallic and non-metallic elements are derived, most of those elements occurred only as apparently insignificant traces. The first stage in their concentration is the crystallising out of vast bulks of common rock-forming minerals, such as pyroxenes, felspars and quartz, leaving a mobile water-bearing residue much richer in the trace elements, which tends to migrate into restricted cavities which are under much less pressure and temperature.

Dissimilar magmas, *e.g.*, those of doleritic and granitic types, differ not only in their major constituents by which they are grouped, but undoubtedly also in the nature and proportion of their trace elements. Further, even otherwise closely similar magmas differ enormously, in different regions, in their content of these valuable traces. Thus it is a reasonable deduction from observed facts that, of many otherwise identical granites, those which are relatively rich in gold, tin, lead or radium are of very restricted distribution. The same may be said of those dolerites and syenites from which important concentrations of gold, silver or copper have been derived; or of those peridotites which have yielded valuable amounts of nickel or platinum. An important step, therefore, in the definition of the metalliferous provinces of any region is the tracing of the boundaries of favourable magmatic intrusions, and this is usually recognised as a fundamental function of official geological surveys.

Fortunately certain intrusive rocks, in restricted areas, contain several times the average proportion, and even, in rare instances, several hundred times this proportion of one or more valuable elements. This is the ultimate basis of many of our metallic provinces.

So far I have only dealt in detail with the second of my suggested fundamental influences. Let us now deal briefly with the first, viz., the nature of the immediate country of certain mineral deposits. I have already referred to its paramount importance in the case of those minerals characteristic only of ultrabasic rocks. Assuming that the elements of certain minerals occurred originally in fluid effluents from igneous magmas, these vapours or solutions would preserve their stability and form no useful deposit unless their equilibrium is upset by changing physical and chemical conditions. Physical changes include reduction of temperature and pressure, which are found in the channels of migration, but are seldom in themselves sufficient to completely serve our purpose, but chemical interaction with the walls of the cavities through which the fluids are moving, and with solutions of different origin seeping into them, is capable of producing heavy precipitation. Thus it is very probable that tin and tantalum migrate from granite magmas in solutions in which they are in equilibrium with fluorine, and which are stabilised by excess of hydrofluoric acid. Such solutions are completely altered by contact at lower temperatures with reactive compounds of alumina and lime, which interact with the fluorine radicle, and allow the tin to hydrolyse to tin oxide (cassiterite), and the tantalum in the presence of available iron, manganese or yttrium to form stable compounds with those metals devoid of fluorine.

Again, gold appears to arise in many instances from a magma as a sulphaurate ion in equilibrium with potassium in a neutral or alkaline solution. Such solutions are most readily affected by certain iron compounds such as ferruginous chlorites, magnetite and haematite, the result being the simultaneous precipitation of pyrite or pyrrhotite and metallic gold. Quite frequently the original magmatic solutions include the sulpharsenite ion, in which case the same causes produce a precipitation of metallic gold and arsenopyrite, the latter the most important source of commercial arsenic.

Again inverting the order of my original postulates, my fourth fundamental influence was the burial of mineral bearing formations with later ones of sedimentary or volcanic origin. Where this burial is not too deep, *e.g.*, in the case of the auriferous deep leads of Victoria, which have been buried beneath barren flows of basalt, it has often been found possible to deduce the existence of possibly payable ore beneath the later cover and to mine it economically. In the case of petroleum this burial of the valuable strata is essential to the preservation of oil supplies through geological ages for our present use, and by boring on systematic lines the oil reservoirs are located and controlled within bounds during commercial exploitation. Coal, rock salt, potash salts and boron salts are further instances where the preservation by geological burial has been of the greatest value to mankind.

On the other hand there are many instances where metalliferous rocks have been traced up to the boundaries of an old formation, and then completely lost beneath a thick series of more recent barren sediments, thus seriously restricting a metalliferous province. Many instances of this will recur to you in our own State, especially in regard to our main gold province.

The last of my fundamental influences is that of the dynamic history of the region under consideration, which leads us to the second section of my address viz., that dealing with metallogenetic epochs. It is obvious that if the vapours and solutions containing valuable elements are to migrate and be precipitated for our benefit in concentrated form, there must be cavities, *i.e.*, connected pores and more or less complex fissures, through which the fluids can move. In the case of metals derived from underlying and surrounding magmas these fissures must penetrate to great depths and horizontal distances. All of this demands more or less violent crumpling or cracking of the earth's crust from time to time, such as arises from its slow adjustment to the changes of volume brought about by the opposing influences of the radiation of original internal heat, and the accumulation of new heat generated by the disintegration of unequally distributed radioactive elements.

METALLOGENETIC EPOCHS.

The processes of concentration of valuable deposits of metallic ores and other minerals in lodes and beds has not been a continuous one throughout the ages. On the contrary, preceding and succeeding long periods of inactivity, there have been well marked epochs during which the concentration of various minerals has been in active operation in one or other portion of the globe where the optimum conditions for the time prevailed.

For those minerals which are direct segregations within the masses of magmas, these times have been those of the intrusion of the right type of magma towards the surface of the earth and its period of cooling there.

For gold and other mineral deposits in the form of deep seated lodes, the active epochs have been those of intense dynamic changes in the earth's crust, such as appear to be taking place at the present day for example in Japan. Only during such periods, of which four major ones have been well defined in Europe and North America, do the necessary conditions arise for extensive lode formation. These include the crumpling of the earth's crust to great depths, with consequent deep seated fissuring, and the extrusion of magmas into much higher zones in the anticlinoriums. This is followed by the cooling and crystallisation of the magmas, with the emission of heated vapours and liquids, in which their trace elements have been concentrated as in a natural brine.

In Europe and North America the four major epochs which have been recognised, are named as follow: [10]

Age.	Europe.	N. America.
Precambrian	Charnian	Killarnean
Silurian	Caledonian	Taconic
Carboniferous	Hercynian	Appalachian-Ouachita
Tertiary	Alpine	Cascadian-Laramie

Other minor "revolutions," as they have been called, are probably of minor importance in respect of ore formation. In the South-Eastern States of Australia the Silurian revolution of the Northern Hemisphere seems to have been deferred to Devonian times, when it was accompanied by a major formation of gold, tin and other metallic deposits. [11, 17] The deposition of gold, which has such a fascination for all of us, is especially associated in many parts of the world with the Precambrian and Tertiary orogenic epochs, of which the former is of exclusive importance in this State. Since then the concentration of gold and other valuable metals has been in abeyance here, except for small surface redistributions from outcrops of Precambrian origin. Important non-metallic minerals have, however, been concentrated during several later epochs.

In the case of economic minerals of sedimentary origin, the controlling principles are still those of mineral provinces and metallogenetic epochs, but they have a different aspect to those controlling the accumulations of minerals produced by subsurface circulation. Furthermore the two factors are inextricably interwoven. The favouring conditions in these cases are purely surface ones, such as the nature of existing rock outcrops, the climate, and conditions of erosion, surface transport and sedimentation, the last involving both the chemical and physical conditions of the basins of accumulation. Throughout the world certain ages have produced similar surface conditions with the resultant concentration of similar valuable beds of minerals.

It is not easy to say which are the most important sedimentary minerals, but the list should include at least salt, coal, petroleum, iron ore, limestone, and potash salts. The formation of coal requires a superabundance of rank vegetation, rapid decay, accumulation of the debris in situ, or at a short distance, and finally its burial beneath a covering of mud and sand for sufficient periods to mature from humus into coal. The Carboniferous-Permian and the Tertiary Periods produced these requisite conditions in every continent, and the same times seem to have been most favourable for the development and storage of petroleum. On the other hand, a much earlier period, the Archaean, was the most favourable for the growth of large beds of haematitic and magnetic iron ores in such widely separated areas as Scandinavia, India, Western Australia, Brazil and the north-eastern States of America. Deposits of potash salts and boron salts have severely restricted provinces, and epochs of formation. The most important province of the former is in Central Europe and its epoch, the Permian. Of the boron salts the most important provinces are in the western United States, and Tibet, in both cases the genetic epoch being Quaternary. Rock salt is much more widely distributed both in respect of geographical space and geological age. Still more widely distributed is limestone.

APPLICATION TO WESTERN AUSTRALIA.

After briefly outlining the theory of mineral provinces and metallogenetic epochs, it remains to apply them to the area embraced by the boundaries of our own State.

In general it may be stated that with small exceptions the heavy metal deposits in this State are confined to the various stages of the Precambrian, which limits them in respect of both space and time. Only in rare instances do they rise to the Cambrian, Devonian and Lower Carboniferous. In this connection it is to be noted that the Silurian system, which is of such great economic importance in the Eastern States, has not yet been recognised in this State. Most of the deposits here antedate the Nullagine Series, which in the complete absence of fossils, is thought on field evidence to be of Upper Precambrian age. The most important exceptions are the rise of gold through the lowest beds of the Nullagine Series at a few places in the North-West including Nullagine itself, and through supposedly Carboniferous, Permian or Triassic beds at Donnybrook; and the rise of lead and zinc into Devonian beds at Narlarla, and of lead and copper into Nullagine beds in the North-West. Finally there has been the redistribution in shallow alluvial and eluvial ground of such resistant minerals as native gold, cassiterite and tantalite during Pleistocene and Recent times, and the concentration during the same period of brown iron ore and bauxite in primary laterites.

GOLD IN WESTERN AUSTRALIA.

The accompanying map of the State (Plate 1) shows the actual areas where gold has been raised, as distinct from the much wider areas which for administrative purposes have been proclaimed as "goldfields." The gold bearing area has been mapped primarily on the basis of including as probably gold bearing, and plotting as solid black circles, all ground within a radius of 25 miles of every spot where gold has actually been worked. That having been done it is seen that excluding two or three isolated and unimportant areas it is easy to define one major and one minor gold bearing province. The latter occurs in central Kimberley and covers an area perhaps too liberally extended to cover 20,000 square miles. It has yielded less than 0.1 per cent. of the whole gold output of the State. It has not been geologically mapped in detail, but appears to be confined to an area of Middle Precambrian rocks, possibly associated with some older ones, and to be associated with an intrusion of granite whose outcrop runs N.N.E. between Longs. 127 and 129.

The major gold province stretches from the south coast at Hopetoun to the north coast at Roebourne and covers an area of 250,000 square miles, about one-quarter of the whole State. But for later sediments causing deep embayments on both east and west sides in the northern half, and cutting off a large section on the south-east corner, the actual exposure of gold bearing rocks would be much greater. From the time active gold mining began in 1886 up to the end of 1938 this province has produced nearly 44½ million ounces Troy of fine gold, valued at over £215 million in Australian currency.

Broadly this province may be looked upon as a huge anticlinorium of early and middle Precambrian rocks with a core of granite, the whole having a slight pitch to the north. Later flooding with sediments has considerably modified its primeval boundaries. Though it is not very evident on the map, owing to the liberal boundaries allotted to individual mining areas, all the important gold deposits are confined to the greenstones and sediments forming the flanks of the granite or occurring as infolded "roof-pendents" in it. From the point of view of gold genesis however, the granite core, which includes more than one stage of intrusion, is of the highest importance, since it appears that this is the source from which most if not all of the gold arose. At present it can be traced N.N.W. from the Esperance district across the Eastern railway between Southern Cross and Coolgardie, thence through Central Murchison, at the north end of which it disappears beneath rocks of Mosquito Creek and Nullagine ages, reappearing for a space on the south side of the Hamersley Ranges, and finally showing in central and northern Pilbara.

The time occupied in the accumulation and consolidation of Precambrian rocks has been estimated roughly at 1,000 million years[10], a longer period than has elapsed ever since the youngest of them was formed. To say that gold was mostly deposited in its present position in Western Australia in that era is therefore a very wide and vague limitation of time. Thanks, however, to the researches of our virile Geological Survey, the Geology Department of the University, and a small band of other students of the subject, it is now possible to narrow down this time in several different ways.

Firstly, it is to be noted that except in two very small and unimportant areas near Nullagine in the north and Donnybrook in the south-west, gold has not penetrated upwards into the Upper Precambrian Nullagine Series, or any later series, though the former is heavily invaded by igneous rocks of a basic type, and to a less extent by rhyolites. This sets an upper limit to the main gold depositing epoch, and excludes any correlation with the great Devonian gold producing epoch of the Eastern States.

A lower limit is set by the very widely observed fact that where gold and haematite-jaspilite have been found together, the gold is obviously in every case later than the consolidation of the jaspilite. Evidence not only here, but in such widely separated regions as Canada, Scandinavia and India, place these jaspilites moderately low down in the Lower Precambrian[14 16].

The numerous auriferous quartz veins in the Middle Precambrian Mosquito Creek-Ashburton Series of metasediments, for example, in the type localities, and at Coodardy and Peak Hill, prove that a considerable proportion of the gold concentration must have occurred long after the first intrusion of granite. This is indicated by the fact that a large proportion of the beds of this series consists of typical granite debris and derivatives, which could only have accumulated after an extensive granite mass had reached the surface and, having consolidated, been subject to normal erosive agencies.

Other evidence of time is afforded by the relationship of gold to the extensive development of acid pegmatites penetrating the Lower Precambrian, and the much smaller development in the Middle Precambrian. Both of these were associated with granite intrusions, and the presence of them in quartz-mica schists of the second series, clearly proves at least two important ages of intrusive granite. In the oldest rocks the auriferous quartz veins usually cut the pegmatite veins, although in Yilgarn there are a number of instances, *e.g.*, at Parkers Range, where the reverse is the case. In several instances acid pegmatite veins are themselves auriferous to an important degree, *e.g.*, at Mt. Palmer and Westonia.

Finally, there are a number of more or less important gold mines, such as Tindals at Coolgardie, Red Hill at Kanowna, and Patricia at Edjudina, which are actually mining porphyry dykes traversed by a network of contemporaneous quartz veinlets, the whole mass being payably auriferous.

It would appear then that the principal gold-producing epoch was associated with an extensive granite intrusion along the axis of the principal province, beginning towards the close of the Lower Precambrian period. It started with the first formation of porphyry dykes and pegmatite veins and continued on till after most, but not all, of these extrusions from the granite magma had ceased to find deep-seated channels reaching upwards towards the surface.

A later epoch of gold deposition of less importance may have been contemporaneous with a second, less extensive, upwelling of granite in late Middle Precambrian time, with a final small dying spurt in early Upper Precambrian time. The former of these, typified by the valuable Coodardy and Peak Hill occurrences, are associated with a very minor formation of acid pegmatite veins and apparently no intrusion of porphyry dykes. On the other hand, the earliest gold veins, such as those of Kalgoorlie, Meekatharra and Wiluna are invariably closely connected with large porphyry dykes. These latter deposits are usually not associated with pegmatite veins, being characteristic of an earlier and hotter period of igneous intrusion, causing extensive metasomatism along the zones of fracture.

Several types of metasomatism, *i.e.*, the chemical alteration of a rock mass, are evident as the result of the impregnation of the older rocks with gold, and these shed considerable light upon the physical and chemical conditions under which the gold was introduced and deposited.

Immense pressures are indicated in many cases by the forcing of the gold-bearing fluid along microscopic fracture planes of such dense rocks as amphibolites, hornblende schist and chlorite schist. It has even been capable of penetrating between individual crystals of the densest rocks, producing metasomatic replacements with gold deposition at a distance from any even microscopically visible fissure. Comparatively high pressures and temperatures are also indicated by the formation of such secondary minerals as tourmaline and scheelite.

Of chemical changes accompanying gold deposition there is widespread evidence of (1) sulphidation, (2) silicification, (3) carbonation, (4) micacisation, (5) chloritisation. These alterations are not mutually exclusive, but in many instances concurrent. From the nature of things, the component minerals of greenstones are more susceptible to chemical change than those of acid igneous and siliceous sedimentary rocks. The alteration of old dykes, lava flows and tuffs derived from gabbro and peridotite is much more severe in the vicinity of gold veins than that of granites, gneisses, slates and mica schists. Incidentally, this severe alteration of greenstones by auriferous fluids was necessarily accompanied by equally extensive alterations in those fluids themselves, and so favoured the local deposition of gold from them.

Dealing briefly with the various types of metasomatic change, *sulphidation* involved the formation of pyrite, arsenopyrite, and less often pyrrhotite through interaction of amphibole, chlorite, magnetite, haematite and other iron-bearing minerals with sulphur and arsenic bearing ions in the fluids. As there is a mass of evidence pointing in very many cases, notably at Kalgoorlie, Wiluna and Mt. Magnet to the introduction of gold as the sulphaurate ion $(AuS_2)^-$, the tendency of the iron-bearing minerals particularly chlorite and magnetite to combine with the sulphur of this ion must have been a major cause of the precipitation of gold in or alongside the sulphide minerals. Most noteworthy and significant in Murchison is the enrichment of gold in veins where they cross magnetite jaspilite bands, with simultaneous conversion of magnetite into pyrite.

Silicification.—In addition to the almost universal deposition of quartz with gold in open fissures to form the typical reefs, there are many instances of the impregnation of auriferous crush zones with chalcedony in the form of metasomatic replacements of the original minerals, *e.g.*, at Marble Bar and Kalgoorlie.

Carbonation is a widespread phenomenon in gold deposits in greenstones, considerable proportions of calcite, ankerite and occasionally magnesite, occurring as replacements of labradorite, amphibole, chlorite and antigorite in the veins of Warrawoona, Wiluna, Meekatharra, Reedy, Leonora and Kalgoorlie, to mention only a few typical examples.

Micacisation.—The development of secondary sericite along the lode channels, often in rocks originally very deficient in potash, indicates the large quantity of potash in solution in the auriferous fluids. It is frequently associated with carbonation, as in the six localities cited in the last paragraph, but in some places, *e.g.*, Burbanks, has been found without carbonation. In the latter case, as well as at Menzies, biotite is formed rather than muscovite, a result to be expected when the original iron and magnesia are not converted into carbonates.

Chloritisation appears in many instances to have preceded and accompanied gold deposition, pyroxenes and amphiboles being converted *in situ* into corresponding chlorites, and small nests and films of chlorite being formed in auriferous quartz veins.

At this stage it is pertinent to consider the form in which gold has been introduced into its present position, a matter briefly referred to above under "sulphidation." Most authors dealing with this and other regions consider that gold was brought in from the granite magma in acid or neutral solutions of gold chloride, and instance its precipitation, *e.g.*, in Victoria, in proximity to graphitic zones of rock. In Western Australia graphitic rocks are widespread in the rock complex within gold mining areas, but in no instance of which I am aware has any gold been found either impregnating the graphite rocks, or concentrated at contacts with them. On the contrary, iron oxides and silicates, which would be expected to upset the equilibrium of a sulphide solution of gold are invariably, one or the other or both, present in abundance. My own theory is that gold was introduced into its present situation in the form of an alkaline or neutral solution of potassium and sulphaurate ions (K-AuS_2) in mutual equilibrium. This theory was briefly outlined by the author in 1912 in a study of the gold ores of Kalgoorlie[7]. Twenty-seven years' further study has confirmed it completely. The chief arguments in favour of it are: (1) gold is soluble in potassium sulphide solution to form potassium sulphaurate, (2) the equilibrium of this solution is upset, and gold precipitated, not by graphite, but by oxidising agents, and by compounds of metals, such as iron and copper, which combine readily with sulphur to form stable compounds; (3) gold is actually found in association with oxygen-bearing iron compounds of the original rock which have been in part sulphidised during ore deposition, particularly haematite and magnetite to pyrite, and ferruginous chlorite to a bleached mixture of pyrite or pyrrhotite, and a magnesian chlorite or sericite; (4) in all the typical metasomatic greenstone lodes there is a marked increase in potash content, with a development of sericite, or occasionally biotite, neither mineral a constituent of the original rock. This theory furthermore explains the simultaneous occurrence of tellurides and arsenopyrite in some cases, since the ion AsS_3 would certainly be stable and unstable under the same conditions as AuS_2, and presumably also the ion TeS_3.

COPPER.

In a comparative sense no really large copper concentration has yet been found in any part of the State, only four deposits being of any serious importance. The total production of ore has been 270,000 tons, valued at a little under £2,000,000. More than one-half of this was produced between 1901 and 1920, since when the industry has waned considerably.

Although copper, like gold, has been found practically entirely in Precambrian rocks, and by far the greater part in association with the same vast anticlinorium stretching from Pilbara to Phillips River, there are important differences in the distribution of the two metals both in space and time. As the latter affects the former, it will be dealt with first.

According to field authorities* there is very little doubt that many copper ore occurrences in the northern part of the main province, *e.g.*, south of Roebourne and throughout the Ashburton Valley, are in Nullagine beds of Upper Precambrian Age. Rocks of this age have not been defined with certainty in the lower part of the province, so that the age of the lodes traversing the Lower and Middle Precambrian beds in that region cannot be fixed within close limits.

It is to be noted that whilst at Ravensthorpe, Roebourne, and some parts of the Ashburton Valley the same veins yield important amounts of both copper and gold, elsewhere copper ores are very poor in gold. Again, the latter metal for the most part does not extend upward into the Upper Precambrian, which points to the introducion of copper beginning when that of gold was waning, and continuing for a long period after gold had ceased to be concentrated in veins.

* T. Blatchford, H. A. Ellis, K. J. Finucane, *et alia*.

There is good reason to believe that copper is derived from doleritic, and not from granitic magma, hence its association with the same central granite upheavals as gold is due not to the granite being the source of the metal, but to the extensive fissuring and dislocation accompanying its upthrust. These dynamic changes permitted the intrusion of dolerite magma and the subsequent derivation of copper ores from it. It is known in fact that extensive dolerite intrusions occurred in the Nullagine Period, and this must be considered the main copper producing epoch in the State's history.

Turning to the map (Plate 2) illustrating the distribution of copper, where again actual mines and workable deposits are indicated by solid black circles, we note first small isolated areas of copper-bearing rocks in East and West Kimberley. The main copper province, however, overlaps the main gold province as regards three-quarters of its area, but differs to an important degree in not extending so far to the east between Lats. 27 and 31, and on the other hand in having a wide extension towards the west in the same latitudes. In detail it is to be noted that there have been much fewer productive centres of copper than of gold, and that these tend to be distributed round the periphery of the province. In fact, the four most important producers of copper, Whim Creek, Murrin, Ravensthorpe and Northampton, are on the extreme borders of the province. So, too, are the less important centres at the head, and near the mouth, of the Ashburton River.

We are led then to the important generalisation that new copper deposits of value are most likely to be found round the periphery of the major province as outlined.

LEAD AND SILVER.

A glance at the map (Plate 3) which illustrates the lead occurrences in the State shows an entirely different distribution to that of gold and copper. This is of course viewing the occurrences from an economic standpoint, and taking into account that it takes several hundredweight of lead to have the same value as a single ounce of gold. As a matter of fact lead in proportions of the same order as that of gold (*i.e.*, in pennyweights to the ton), is widespread in the auriferous veins of the main gold province, and are looked upon by miners in many places as indicative of payable gold ore. These amounts are not economically recoverable, and are therefore negligible for our purpose.

Lead in commercially valuable quantities is so far known to occur only in three small provinces. The largest in point of area, though not in point of production, is one covering about 50,000 square miles in the Pilbara-Ashburton region. This includes the two important centres of Braeside and Uaroo. The next largest, but least productive, is in East Kimberley, and covers about 15,000 square miles. The smallest, but by far the most valuable up to the present, is the Northampton area covering only about 1,000 square miles.

Except for the unique Narlarla lead-zinc segregation veins in Devonian limestone (in West Kimberley) the lead producing epoch appears to have been co-extensive with, to slightly later than, that of copper, veins containing the two metals, either separately, or in conjunction, being often associated. The order gold-copper-lead represents the upwards sequence in time of concentration of the three metals, the copper epoch overlapping partly those of both other metals. Lead veins are mainly found in Middle and

Upper Precambrian rocks. In the Northampton area, where most detailed investigation has been done, galena and chalcopyrite are frequently found together in quartz veins and impregnations in garnetiferous paragneiss. They are closely associated with acid pegmatite veins and dolerite dykes.

In the Northampton district only traces of silver occur with the lead. In the Pilbara-Ashburton province on the other hand important amounts of silver accompany the lead, and it is this area which has yielded practically all the silver-lead ore which appears in the official statistics. Many of the East Kimberley lead ores are also rich in silver. All the "metallic silver," as distinct from "silver-lead," recorded in the statistics, which constitutes quite three-quarters of the total output of the metal, has been derived from the comparatively insignificant amounts alloyed with gold in our gold ores.

The statistics to the end of 1938 are approximately as follow:

Lead concentrates, 115,000 tons	£A. 1,700,000
Silver, 5½ million ounces	700,000

TIN, TANTALUM AND NIOBIUM.

The distribution of ores of these three metals is coincident, since they are genetically closely related. It is recognised however that the relative proportions of the metals may so vary from place to place that an area of value for its tin ores may be of little value for its tantalum or niobium ores, and vice versa. In some districts too tantalum predominates over niobium, in others the reverse condition prevails. As concentrates rich in tantalum have averaged £700 a ton in value, those rich in tin £105 a ton, and those rich in niobium only £70 a ton, this variation is of considerable economic importance.

These metals are derived in Western Australia from intrusive granites, usually those in which soda predominates over potash. They are confined to the pegmatite veins (and their detritus) which have developed round the margins of the granites and the greenstones into which they are so often intrusive. They appear to have been introduced into the veins as vapours or solutions of the corresponding metallic fluorides, whose stability was upset by the formation of lepidolite or other micas, topaz, and apatite.

Only one determination has been made of the age of these veins. This was of the most important tantalum bearing vein at Wodgina, which was found, by examination of a certain uranium mineral, to be 1,260 million years old, thus placing its formation low down in the Lower Precambrian era, the earliest stage of which has been placed at about 1,500 million years ago. Deposits in other parts of the State appear to be either of similar age or of later age up to the commencement of the upper Precambrian era, rocks of which age do not contain tin or tantalum veins in this State.

In Kimberley there are three or four small isolated occurrences of tin, in one of which it is associated with tungsten (Clara Hill), in the other with tantalum and niobium (Mt. Dockrell). These have been combined in a province covering about 15,000 square miles of Middle Precambrian rocks. (See Plate 4.)

The most important province is in Pilbara, and covers also about 15,000 square miles. This includes Wodgina, Strelley, Moolyella, and a number of smaller mining centres in which tin, tantalum and niobium occur together in varying proportions, mostly in Lower Precambrian rocks.

Another province occurs in the South West covering about 10,000 square miles. Near its southern end is Greenbushes, a very important source of tin, and a minor one of tantalum.

Three other provinces of little economic importance so far are shown on the map, one between the Ashburton and Gascoyne Rivers, another in the Murchison, and a third in the Coolgardie region.

The total production of tin and tantalum ores to the end of 1938 is:

Tin concentrate	15,700 tons — value	£1,650,000
Tantalum and niobium concentrate	267 tons — value	£180,000

IRON.

The definition of iron provinces in the State is not yet possible for several reasons. Iron minerals of one kind and another are universally distributed throughout the land, and until a decision has been reached as to what grade of iron ore is economically workable, it is impossible to draw boundaries to areas containing them. Furthermore only a very small number of our jaspilite haematite-magnetite lodes, and lateritic brown ore beds, have been sampled and assayed to determine their grade. On the accompanying map (Plate 5) an attempt has been made to plot the more important deposits of which any accurate data are available. It is necessarily very incomplete.

The age is not so difficult to determine. The jaspilite ores, containing haematite and magnetite, occur low down in the Lower Precambrian, and are probably contemporaneous with the enclosing rocks. A certain decision on this point awaits the solution of an identical problem in every Precambrian shield throughout the world. Their distribution is co-extensive with the Lower Precambrian volcanic greenstones, but a large proportion of them are too poor in iron, and too rich in silica, to be looked upon as commercial ores.

Of different age is the largest known iron ore body in the State, viz. that at Yampi. This is a true sedimentary bed, or series of beds, composed of rolled grains of magnetite more or less completely altered into haematite, forming part of a series of Middle Precambrian sediments, which defines its age.

Of a quite different type and origin are certain iron sulphide lodes, mainly pyrite and pyrrhotite with some magnetite and iron bearing silicates, whose oxidised outcrops contain important quantities of brown iron ore. These appear to occur in Middle Precambrian rocks, and to be of somewhat later age than the enclosing rocks. At one place, Parker's Range, they are accompanied by extensive veins of iron carbonate.

Finally there are the sporadically distributed patches of high grade brown ore in the extensive bauxite duricrusts, which are of Post-Tertiary age, and possibly still growing.

The only production of iron ore in the State has been that required for a flux in lead and copper smelting, which is thought to have been about 60,000 tons. In addition about 75,000 tons of pyritic ore have been used in the manufacture of sulphuric acid.

MINOR METALS AND METALLOIDS.

Zinc is practically unknown in commercially important quantities in the State, only £5,000 worth of concentrates having been produced. Moderate amounts however occur with lead at Northampton in probable Middle Precambrian rocks, and with copper at Croydon and Murrin in Lower Precambrians. One small zinc lead deposit at Narlarla in Kimberley occurs in Devonian limestones. This is one of the extremely few Post-cambrian ore deposits known in the State.

Antimony is confined to the Lower and Middle Precambrian series of a few isolated centres, only one-third of which have produced commercial parcels of ore. Altogether these have contained about 1,000 tons of the metal valued at £15,000. Except for a few unimportant associations with lead, the antimony has been found to be accompanied by gold in rocks of either Lower or Middle Precambrian age. The presumption is that the time of introduction into its present position was in each case the same as that of the associated lead or gold. When the distribution of antimony is plotted on the map, the occurrences are found to fall into two provinces, one of about 45,000 square miles in the North-West Region, the second of about 60,000 in the Central Region.

Arsenic is rapidly becoming an important product of the State, about 22,000 tons of white arsenic, valued at £350,000 having been produced to the end of 1938. This has all been obtained from Lower Precambrian rocks, where it has been associated with gold, usually in the form of arsenopyrite. A little also occurs as cobaltite, tennantite and enargite. These minerals have all been formed at approximately the same time as the older gold deposits in which they occur. Insignificant amounts also occur with tin ores, in one case in Middle Precambrian rocks. The main genetic epoch, or epochs, was then from the later part of the Lower Precambrian to some time in the Middle Precambrian.

Omitting a few isolated areas unlikely ever to yield commercial quantities of arsenic, the known occurrences may be grouped into the two provinces shown on the accompanying map. (Plate 6.) The central one is the more important and embraces about 150,000 square miles of the central Precambrian shield. The smaller one in the North-West has not yet yielded any commercial supplies, but may do so in the near future.

Tungsten is known only in a few small isolated places stretching from West Kimberley to Norseman, of which the most important appears to be Comet Vale. In several places it occurs without other metallic associates, but more often it is found with gold, with which it appears to be contemporaneous, in rare instances it occurs with molybdenum or tin. The latest rocks it occurs in are Middle Precambrian, and its time of formation corresponds probably with both early and late gold epochs. The production to date is insignificant.

Chromium in the form of chromite so far is known in commercial quantities only in the small area at the east end of the Hamersley Range, where it is contemporaneous with the Lower Precambrian serpentine in which it occurs as segregations. Small quantities of chromite, fuchsite, and miloschite are however found in serpentines of several probable ages in many other parts of the State, and in any of these commercial supplies may one day be located.

Manganese has been worked on a very small scale in Murchison (Horseshoe) and on the South Coast (Ravensthorpe, Eyre Range). There are no data on which to base a map of its distribution, or form an opinion as to its age of formation.

EARTHY MINERALS.

The theory of mineral provinces and metallogenetic epochs may profitably be applied to certain non metallic minerals, *e.g.*, diamond and asbestos. The latter affords the best example so far as this State is concerned.

Asbestos is not the name of a single mineral species, but of a group of silicate minerals, conveniently associated in commerce because they all possess the same finely fibrous structure, with tough and flexible fibres, and can be applied to similar uses. In this State there are three main species of economic value, viz., chrysotile (a highly hydrous silicate of magnesium), anthophyllite (a slightly hydrous silicate of magnesium) and crocidolite (hydrous silicate of sodium and iron). The occurrences of these three minerals are now sufficiently well known for us to be able to allot to each a definite mineral province and a probable age of formation. (See Plate 7.) Crocidolite for instance is confined to the Upper Precambrian (Nullagine) rocks of the Hamersley Range.

Several other earthy minerals of economic importance such as coal, graphite and glauconite could be dealt with in the same way. The distribution of the first, which is of such great importance, has been plotted on the same map as that of asbestos. It is confined to beds of Permian and Miocene age, and to the South Western region of the State.

CONCLUSION.

What is the practical application of all this observation and deduction?

I think it will be realised that from the administrative standpoint in the planning of all new railways, main roads and water supply schemes not only the existing population, but the probable future trend and intensification of population must be considered. There is a considerable amount of data regarding rainfall, soils, crop yields and pastures available to predict the future trend of agriculture. Timber areas too are closely defined. But it has appeared to me that the data regarding mineral resources had not previously been correlated and plotted in a way that would enable present and future Governments to consider the directions in which the mining industry is likely to continue and to expand. Some attempt has been made here to remedy that defect.

Manufacturers too are, and always will be, in need of a guide as to where their factories should be situated in order to be within economic reach of their raw materials.

Finally mining is a business like any other mainly pursued to afford an adequate living to a large number of people, and a possible fortune to the lucky few. I do not think it is in the interests of either the individual or the country at large that the money and energy of any section of the mining community should be expended in directions which are either uneconomical or predoomed to utter failure. I am in hopes that my definition of the distribution of the State's economic minerals in space and time will not only guide the prospector to continue his search within the favourable limits, but will also serve to prevent the waste of valuable capital, both of wealth and of energy.

REFERENCES.

(1) Von Cotta, B.: Die Lehre von der Erzlagerstätten. Freiberg. 1859. English translation, F. Prime. New York, 1870.

(2) Phillips, J. A.: Treatise on Ore Deposits. London, 1884.

(3) Posepny, F.: Genesis of Ore Deposits. New York (1893-1902).

(4) Van Hise, C. R.: Some Principles controlling the Deposition of Ores. New York (1900-1902).

(5) Lindgren, W.: Metasomatic Processes in Fissure Veins. New York (1900-1902).

(6) Montgomery, A.: Some Geological Considerations Affecting Western Australian Ore Deposits. *A'asian Inst. Min. Eng.* 1909.

(7) C. G. Gibson and E. S. Simpson: The Geology and Ore Deposits of Kalgoorlie. (*Geological Survey Bulletin* 42). Perth, 1912.

(8) Maitland, A. Gibb: Mining Handbook of Western Australia. Perth, 1919.

(9) Clarke, F. W.: The Data of Geochemistry (5th Edition). Washington, 1924.

(10) Holmes, A.: The Age of the Earth. London, 1927.

(11) David, T. W. E.: Explanatory Notes to Accompany a New Geological Map of Australia. Sydney, 1932.

(12) Ellsworth, H. V.: Rare Element Minerals of Canada. Ottawa, 1932.

(13) Crook, T.: History of the Theory of Ore Deposits, 1933.

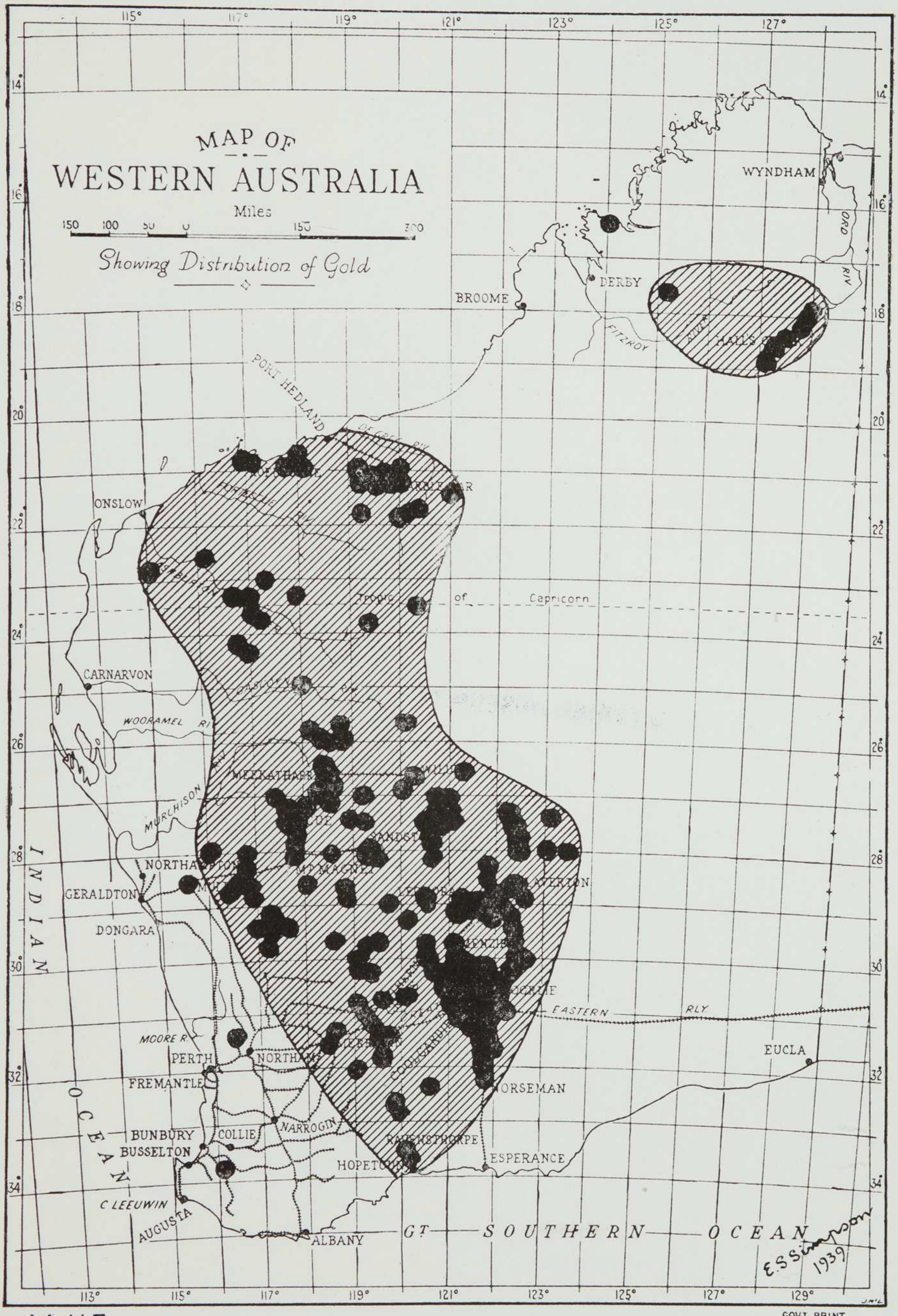
(14) Bruce, E. L.: Mineral Deposits of the Canadian Shield. London, 1933.

(15) Fenner, C. N.: Pneumatolytic Processes in the Formation of Minerals and Ores. New York and Washington, 1933.

(16) Blondel, F.: Le Géologie et les Mines des vieilles Plateformes. Paris, 1936.

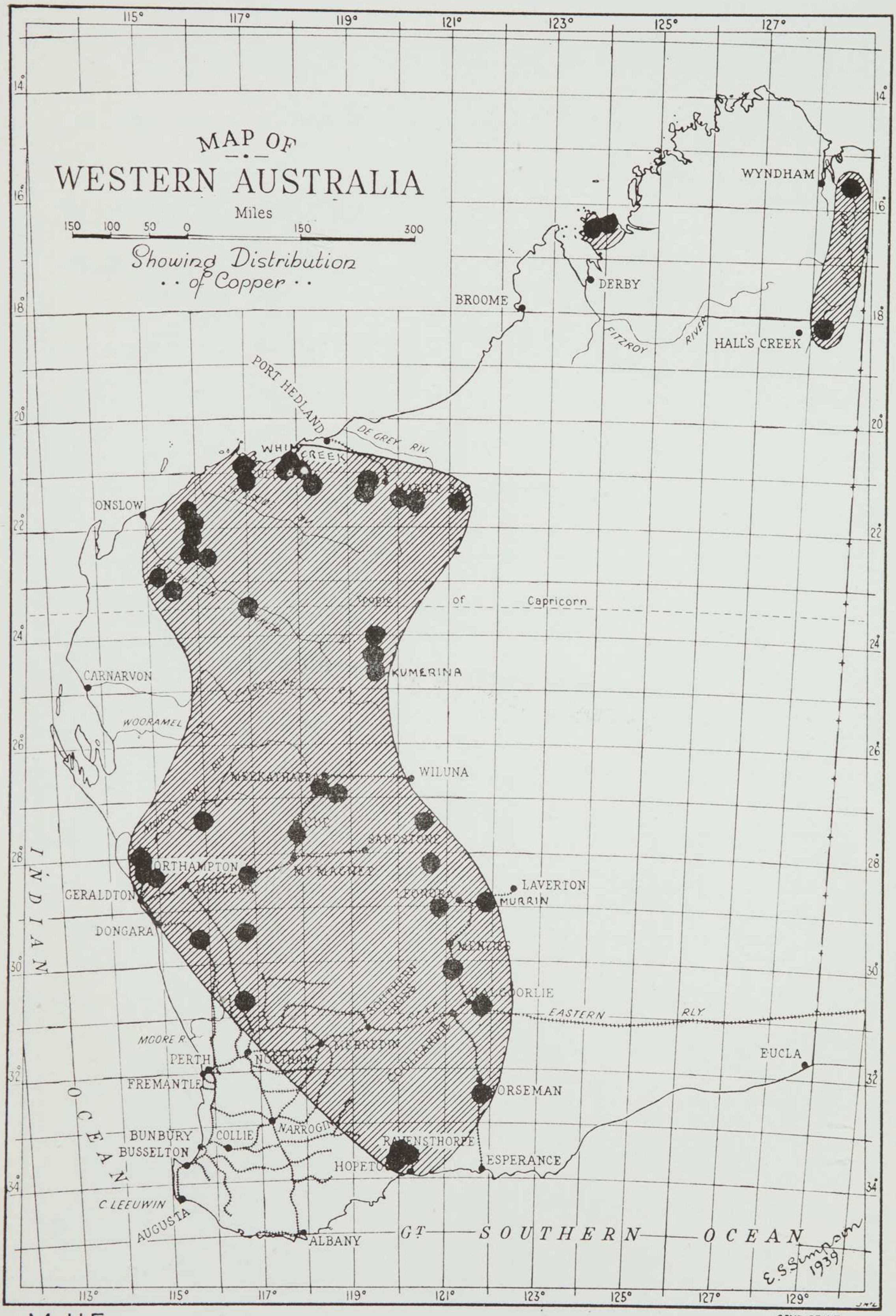
(17) Nye, P. B., and Blake, F.: The Geology and Mineral Deposits of Tasmania. Hobart, 1938.

(18) The Various Bulletins and Annual Reports of the Geological Survey of Western Australia.


MAP OF
WESTERN AUSTRALIA
Miles
Showing Distribution of Gold
WYNDHAM
DERBY
BROOME
FITZROY
PORT HEDLAND
ONSLOW
Tropic of Capricorn
CARNARVON
WOORAMEL RI
MURCHISON
MEEKATHARRA
NORTHAMPTON
GERALDTON
DONGARA
MOORE R.
PERTH
FREMANTLE
NORTHAM
NARROGIN
COLLIE
BUNBURY
BUSSELTON
C LEEUWIN
AUGUSTA
ALBANY
HOPETOUN
RAVENSTHORPE
ESPERANCE
NORSEMAN
EASTERN RLY
EUCLA
INDIAN OCEAN
GT SOUTHERN OCEAN
E.S. Simpson 1939
GOVT PRINT

M 115

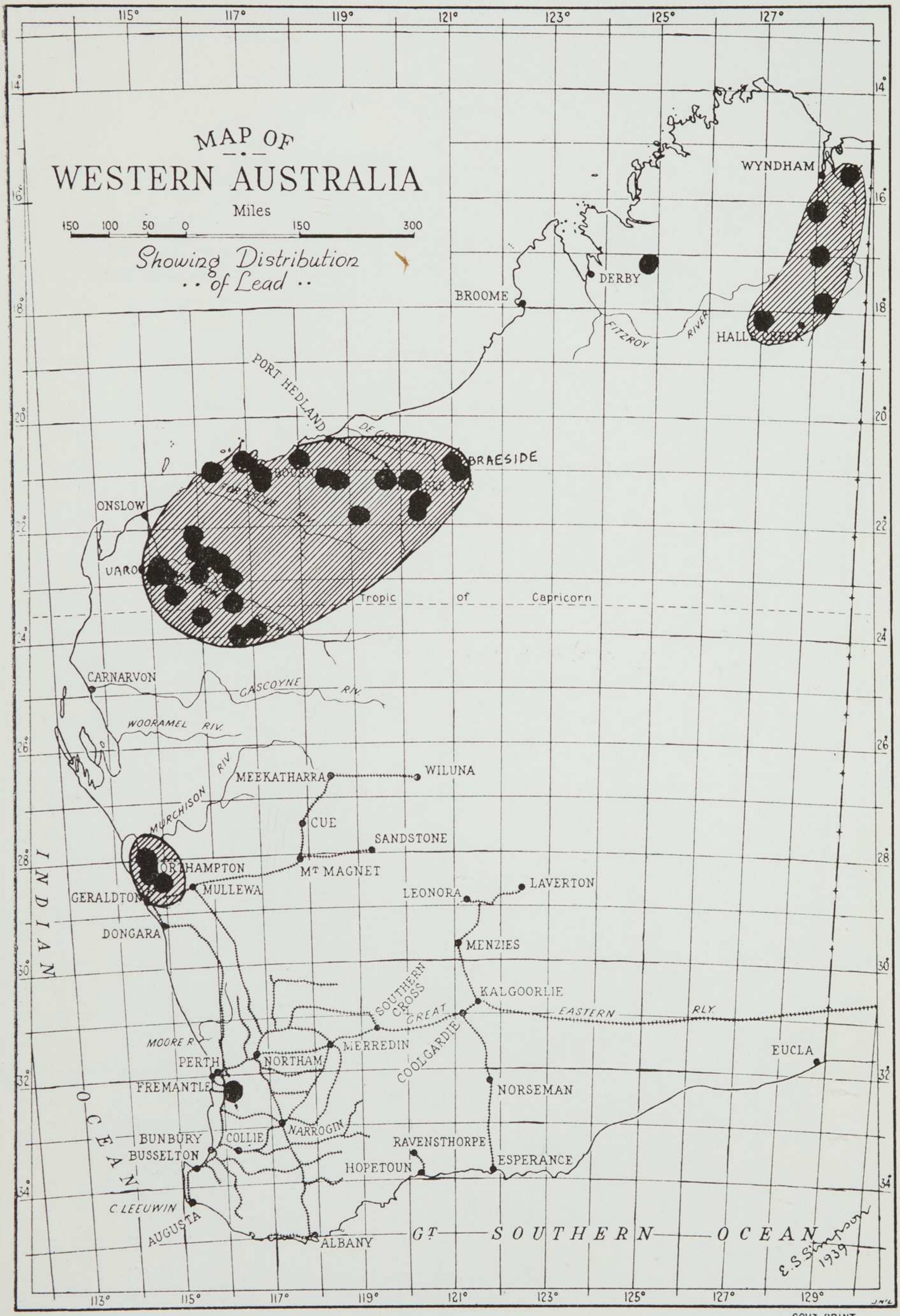
PLATE I.



M 115

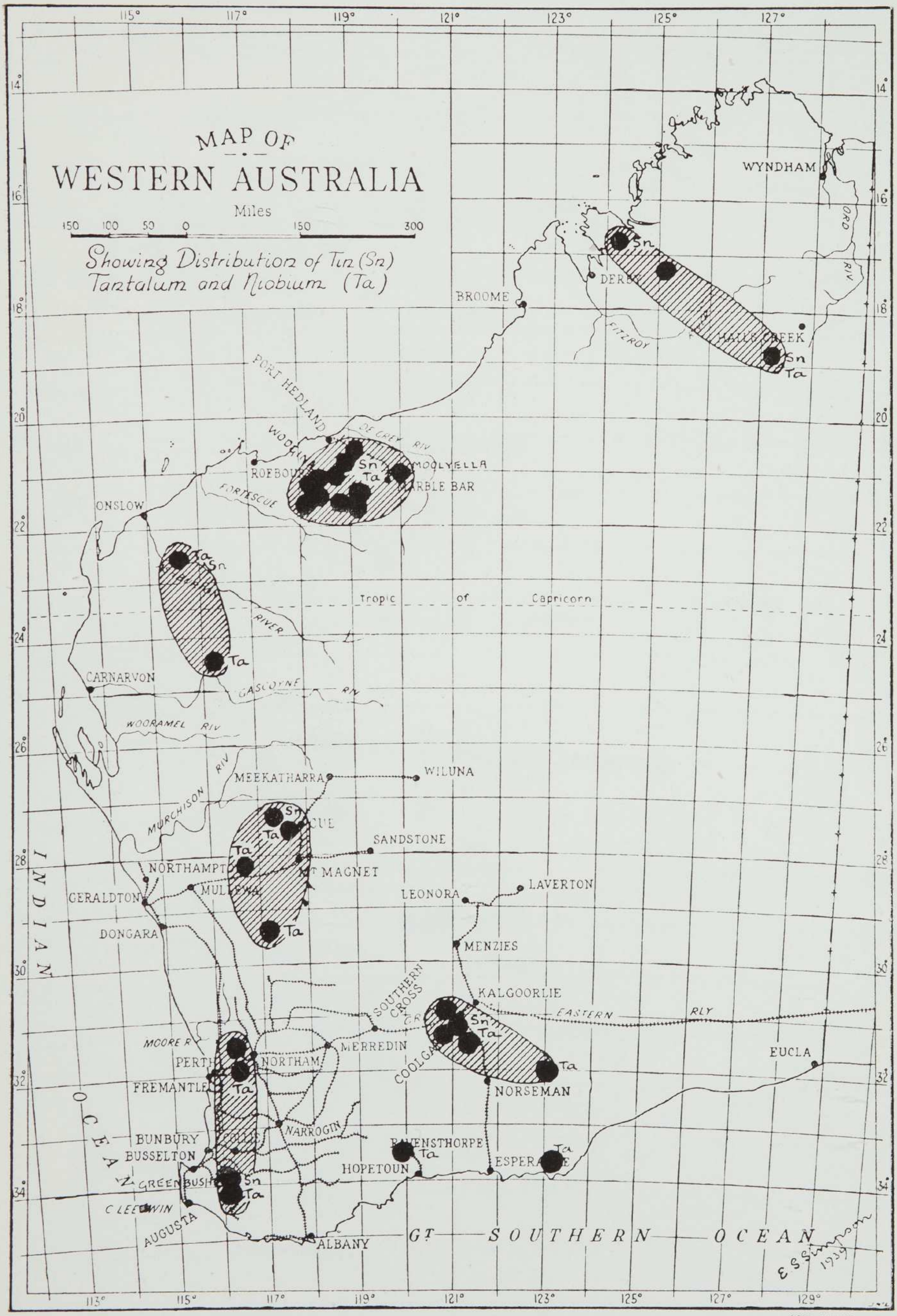
GOVT PRINT

PLATE II.



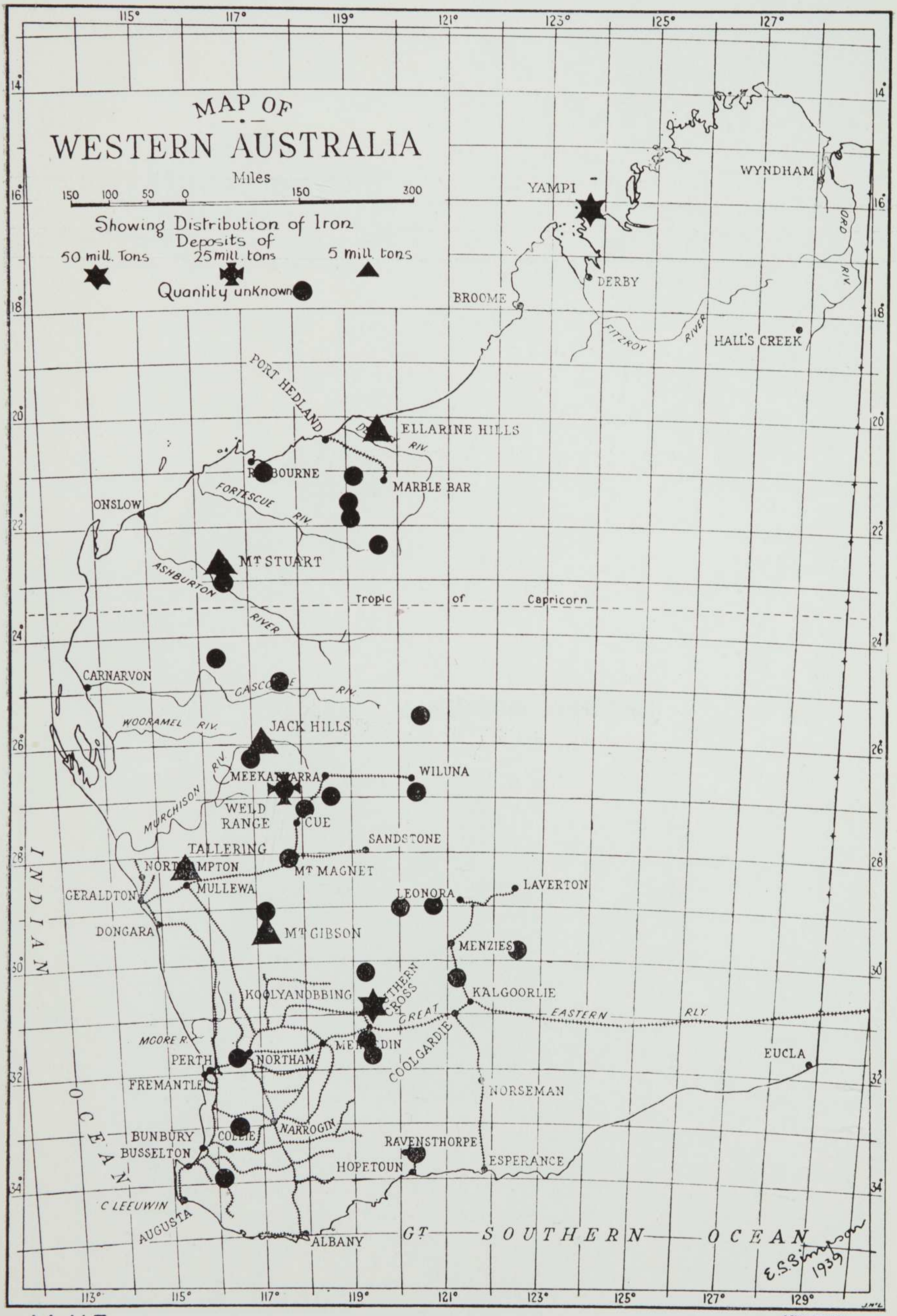
M 115

PLATE III.



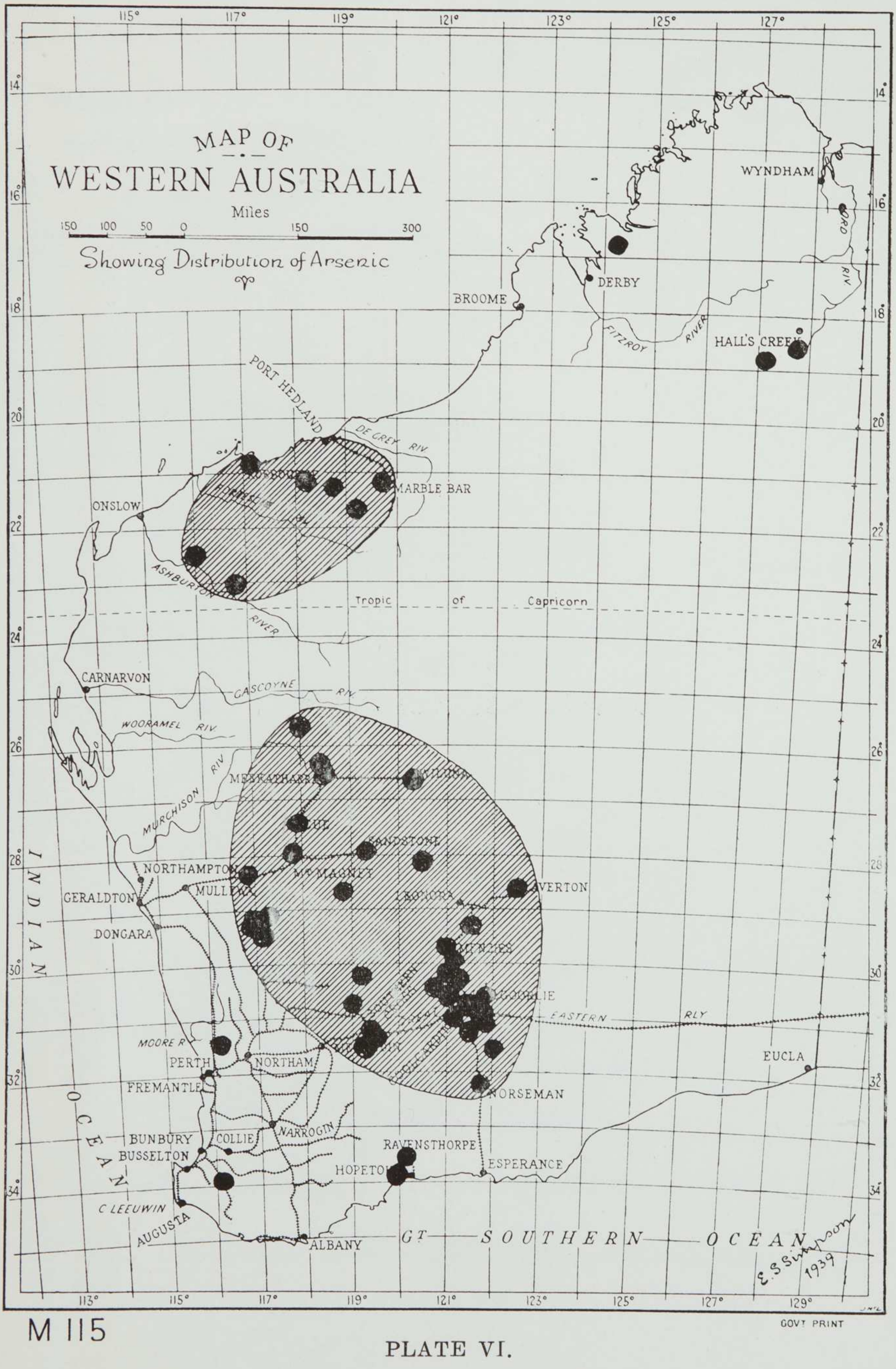
M 115

PLATE IV.


MAP OF
WESTERN AUSTRALIA
Miles
Showing Distribution of Iron Deposits of
50 mill. Tons
25 mill. tons
5 mill. tons
Quantity unknown
YAMPI
WYNDHAM
DERBY
BROOME
HALL'S CREEK
PORT HEDLAND
ELLARINE HILLS
MARBLE BAR
ONSLOW
MT STUART
Tropic of Capricorn
CARNARVON
JACK HILLS
MEEKATHARRA
WILUNA
WELD RANGE
CUE
SANDSTONE
TALLERING
NORTHAMPTON
MT MAGNET
GERALDTON
MULLEWA
LEONORA
LAVERTON
DONGARA
MT GIBSON
MENZIES
KOOLYANOBBING
KALGOORLIE
EASTERN RLY
PERTH
NORTHAM
EUCLA
FREMANTLE
NORSEMAN
BUNBURY
COLLIE
NARROGIN
BUSSELTON
RAVENSTHORPE
HOPETOUN
ESPERANCE
C LEEUWIN
AUGUSTA
ALBANY
INDIAN OCEAN
GT SOUTHERN OCEAN
E.S. Simpson 1939
GOVT PRINT

M 115

PLATE V.



M 115

GOVT PRINT

PLATE VI.

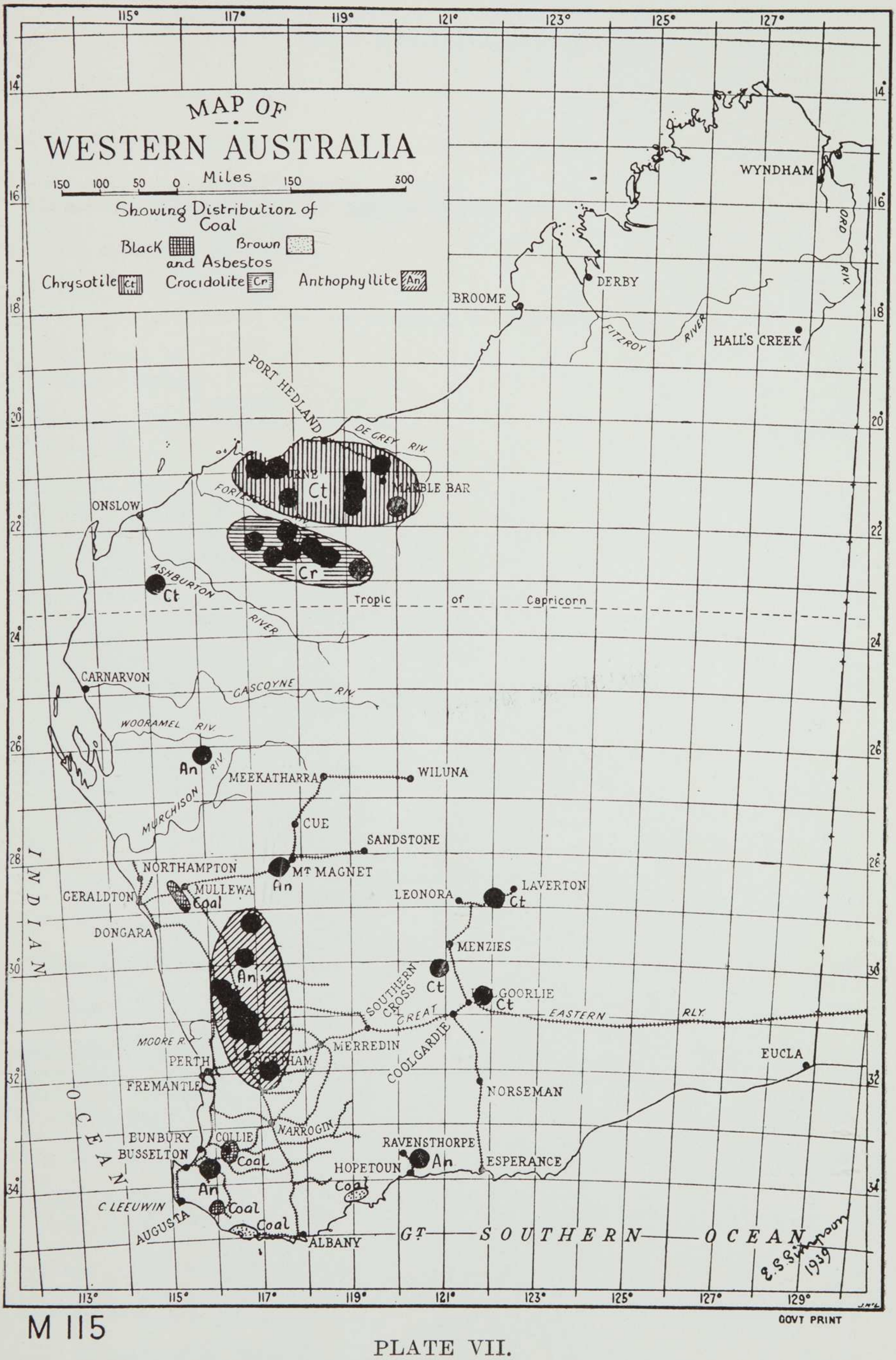

MAP OF
WESTERN AUSTRALIA
150 100 50 0 Miles 150 300
Showing Distribution of Coal
Black Brown
and Asbestos
Chrysotile Ct Crocidolite Cr Anthophyllite An
WYNDHAM
DERBY
BROOME
HALL'S CREEK
FITZROY RIVER
ORD RIV
PORT HEDLAND
DE GREY RIV
MARBLE BAR
ONSLOW
ASHBURTON RIVER
Tropic of Capricorn
CARNARVON
GASCOYNE RIV
WOORAMEL RIV
MURCHISON RIV
MEEKATHARRA
WILUNA
CUE
SANDSTONE
NORTHAMPTON
MT MAGNET
GERALDTON
MULLEWA
DONGARA
LEONORA
LAVERTON
MENZIES
SOUTHERN CROSS
KALGOORLIE
GREAT EASTERN RLY
COOLGARDIE
MERREDIN
MOORE R
PERTH
FREMANTLE
EUCLA
NORSEMAN
NARROGIN
BUNBURY
COLLIE
BUSSELTON
RAVENSTHORPE
HOPETOUN
ESPERANCE
C LEEUWIN
AUGUSTA
ALBANY
INDIAN OCEAN
GT SOUTHERN OCEAN
E.S. Simpson 1939
M 115
GOVT PRINT

PLATE VII.